Thermal-Fluid Coupling Simulation of Ventilation Cooling System of Generator Based on FLOWMASTER

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Abstract: By taking a 2.3 MW double-fed asynchronous generator as an example, a new method for fast simulation analysis of ventilation cooling system inside generator is proposed based on the one-dimensional simulation software FLOWMASTER. The thermal-fluid coupling simulation model of ventilation cooling system inside generator is established. Under the stable running state of the generator, the flow velocity distribution and temperature rise of the key parts of the generator are analyzed. The results prove that the ventilation structure design of the generator meets the temperature rise limit. The simulation results are compared with the theoretical calculation results and the experimental results, which verify the correctness of the thermal-fluid coupling simulation method proposed in this paper.

Key words: large generator; ventilation cooling system; thermal-fluid coupled; FLOWMASTER

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0 Introduction

Research on heating and cooling of generator can provide a reliable basis for real-time early warning and diagnosis of generator failure. With some optimization design theories, it can also guide motor design, reduce production costs and reduce prototype manufacturing cycle. The traditional approach to accurately describe the flow and temperature field inside the generator is using calculation and testing methods to analyze actual operating state of the generator by referring to the motor structure, parameters and operating conditions. With the development of computer technology, computational fluid dynamics (CFD) becomes common method for generator ventilation and heat dissipation. Many scholars have conducted deeply research on the numerical analysis of the large generator[1-2], but are more focused on the analysis of three-dimensional field. FLOWMASTER is an advanced one-dimensional modeling tool widely used in aerospace[3-5], military[6], pipe network[7-8] and other design fields of internal flow system[9]. So far, few scholars have applied this fast simulation software to the simulation flied of large generators. In this paper, by taking a 2.3 MW double-fed asynchronous generator as an example, the thermal-fluid coupling calculation model of ventilation cooling system inside generator is proposed based on FLOWMASTER. Both the flow and the temperature distribution are analyzed during generator steady state operation. By comparing the simulation results with theoretical calculations and experimental results, it is proved that the simulation method has high accuracy and can offer an instruction to the optimization of generator design.

1 Cooling Structure of Generator

In this paper, a 2.3 MW double-fed asynchronous generator is taken as an example. The generator uses back air-air coolers, and its inter-

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nal ventilation system consists of axial and radial ventilation systems. Part of the cooling air from the cooler's outlet flows into the rotor bracket and then flows into the ventilation gap between the stator and rotor along the rotor radial ventilation groove while the other part flows directly into the ventilation gap between the stator and rotor. After the confluence of two streams, the cooling air flows back into the cooler along the stator core radial ventilation grooves. And the heat exchange between the hot air in the cooler and the cold air inside the cooling pipe through the surface of cooling ducts takes away the heat generated by the operation of the generator. The ventilation cooling structure of generator is shown in Fig. 1.

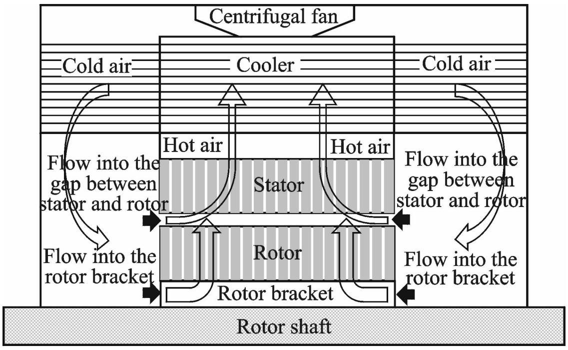

Fig. 1 Ventilation cooling structure of generator

2 Model of Ventilation Cooling System

The use of radial ventilation grooves is the main way to cool the generator. There are 19 radial ventilation grooves in the generator, which means the axial core is divided into 20 sections. In the generator internal modeling, a stator and rotor radial ventilation groove and 1/2 core segments around the groove are handled as a unit. Modeling schematic diagram inside the generator is shown in Fig. 2. So there are 19 units in axial direction and the left and right sides of the middle unit are symmetric. The end section of the core is modeled together with the end of the ventilation duct. Finally, the two parts are integrated into the thermal-fluid coupling simulation model of the generator.

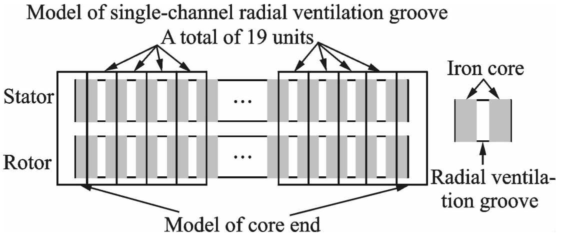

Fig. 2 Modeling schematic diagram inside the generator

2.1 Basic assumptions and boundary conditions

This paper focuses on the internal ventilation and cooling of generators. The internal heat of the generator is considered to be taken away by the cooling air in addition to the bearing surface, which is natural cooling. To simplify the model, only the heat taken away by the cooling air is taken into consideration while the heat loss through the body surface is ignored. And the stray losses are converted to both the teeth and yoke iron loss of stator and rotor and the copper loss of the windings.

Basic assumptions:

(1) The internal structure of the generator and the wind paths are completely symmetrical.

(2) Component loss is concentrated in the center of the geometry.

Boundary conditions:

(1) The inlet air flow rate is determined by the calculation results of internal loss of generator.

(2) The outlet pressure of generator is standard atmospheric pressure.

2.2 Basic theory and control equation

The cooling gas velocity in the generator is relatively low, so it can be treated as incompressible fluid[10]. To solve the thermal-fluid field in the generator, heat convection should be taken into consideration. When the generator is running, there is not only the heat transfer between solids or the cooling gas itself, but also heat exchange between fluid and solid surfaces when fluid flows through the solid which can be expressed by the equation[11] as

$$\frac{\partial t}{\partial \tau}+u\frac{\partial t}{\partial x}+v\frac{\partial t}{\partial y}=\frac{\lambda}{\rho c_p}\left(\frac{\partial^2 t}{\partial x^2}+\frac{\partial^2 t}{\partial y^2}\right)$$

The first item on the left side of the formula is a non-steady state, which represents the change rate of temperature with time. The second term and the third term are expressed as the convection terms, which represent the heat transfer due to flow. The right side of the equation is called a diffusion term, which represents the heat transfer due to fluid heat conduction.

2.3 Heat dissipation model of core end

The heat dissipation model of stator and rotor end established in FLOWMASTER is shown in Fig. 3. The loss of both stator core end and stator winding end is equivalent to a heat flow source when establishing the stator end model. In Fig. 3, the stator end model is shown as component 1. A solid bar, component 2, represents the end of stator core and stator winding. Thermal bridge, component 3, simulates the air duct of stator end. The discrete element, component 4, represents the wind resistance generated by the airflow flowing into the stator and rotor gap. The rotor end model is similar to the stator end model, in which the discrete element, component 8, represents the wind resistance generated by the airflow flowing into the rotor bracket.

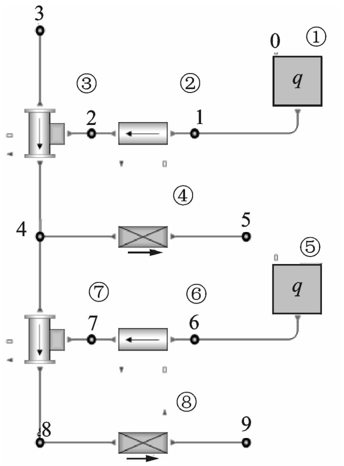

Fig 3 Heat dissipation model of core end

2.4 Thermal-fluid coupling calculation model of single-channel radial ventilation groove

One part of the heat generated by stator winding copper loss dissipates through radial ventilation grooves while the other part is transferred to the stator teeth. On the one hand, the heat generated by the iron loss of the stator teeth dissipates directly through radial ventilation grooves. On the other hand, the heat is transferred to the air gap between stator and rotor, while some of the heat is transferred to the stator yoke. One part of the heat generated by the iron loss of the stator yoke dissipates through radial ventilation grooves while the other part is dissipated through gas chamber at the back of the iron core. Fig. 4 shows the thermal-fluid coupling calculation model of a stator and rotor radial ventilation groove and 1/2 core segments around the groove. Flow sources in FLOWMASTER are used to simulate all types of generator loss. Thermal bridges are used to simulate the wind path through which the cooling gas flows, including the radial ventilation grooves, the air gap between stator and rotor and the gas chamber at the back of the iron core. Solid bars are used to simulate the solid part inside the generator like generator core and winding. Discrete loss components simulate the pressure loss of air ducts. Rotor ventilation slots will produce a rotating rotor head when the generator is running, so rotating pipe is used to simulate its rotation characteristics when establishing the rotor model.

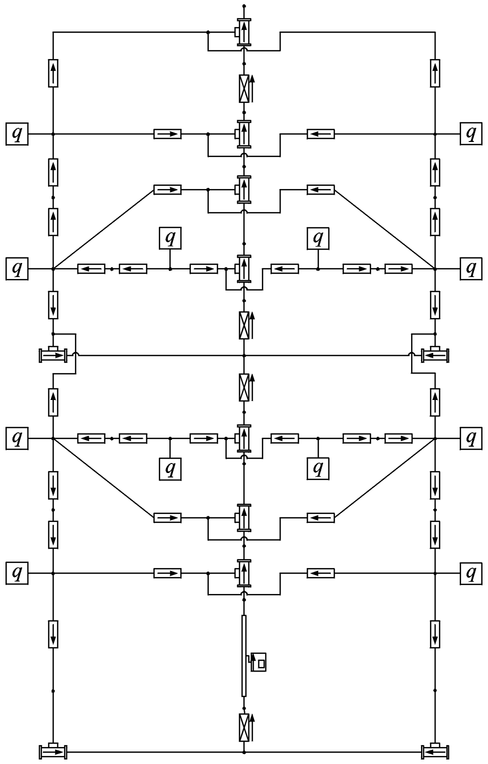

Fig. 4 Thermal-fluid coupling calculation model of single-channel radial ventilation groove

2.5 Whole thermal-fluid coupling simulation model

Fig. 5 shows the whole thermal-fluid coupling simulation model by connecting the heat dissipation model of core end shown in Fig. 3, the thermal-fluid coupling calculation model of single-channel radial ventilating ducts shown in Fig. 4 and the inlet and outlet boundary conditions of the generator cooling system. Cooling gas flows into the generator from both ends of the generator. Then the air flows into the axial ventilation system along air gap between stator, rotor and rotor bracket. And finally it flows out of generator along radial ventilating grooves.

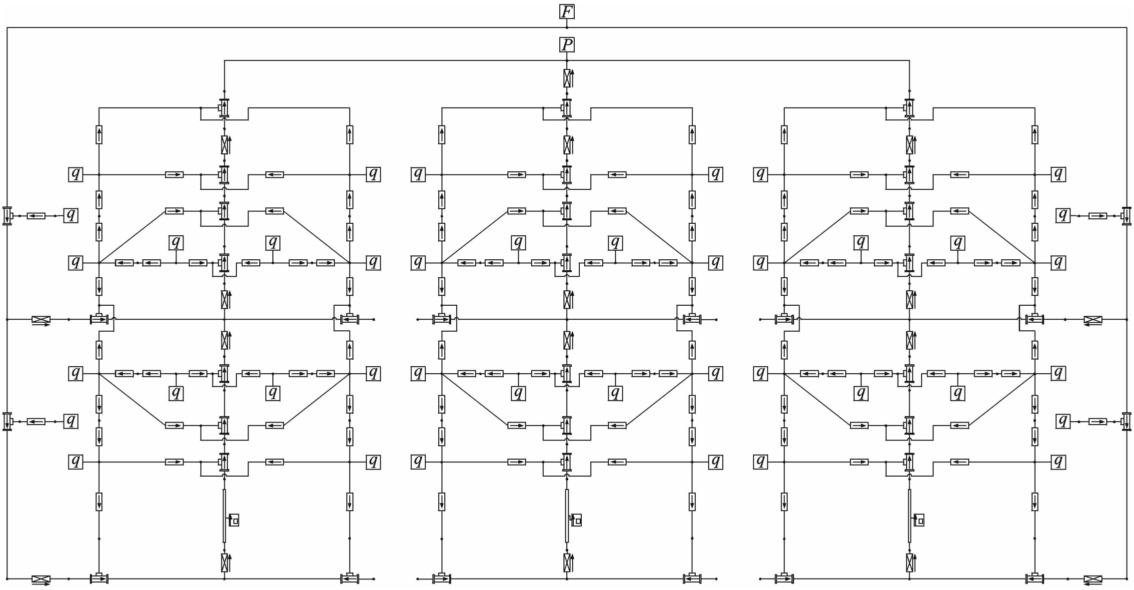

Fig. 5 Whole thermal-fluid coupling simulation model of ventilation cooling system

3 Simulation Results and Analysis

The stable running state of the generator is simulated. During the simulation, the cooling gas flow is the required minimum air flow to take the internal heat of the generator away while the cooling gas temperature rise is 25 K. Due to the symmetry of the generator structure, only the 10 radial ventilation grooves or 10 iron core segments from left to right in Fig. 5 are selected when analyzing the simulation results.

3.1 Flow field distribution

Fig. 6 shows the wind speed in the radial ventilation grooves corresponding to both tooth and yoke of stator, and Fig. 7 shows that of rotor. As shown in Figs. 6,7, for either stator or rotor, the flow rate of the cooling gas in radial ventilation grooves near the end is significantly higher than that in the middle section radial ventilation grooves. This is because the closer the radial ventilation grooves are to the middle position, the less cooling air can reach. For single-channel radial ventilating groove, the wind speed corresponding to yoke is obviously smaller than that to teeth, which is due to the larger ventilation area of yoke.

Fig. 8 shows the rotational pressure head distribution of the radial ventilation groove of the rotor. According to the simulation results, the average rotational pressure head of the radial ventilation grooves is 638.3 Pa while the theoretical calculation result is 727.89 Pa. The difference is 12.31%, which means the simulation results have a certain reference value.

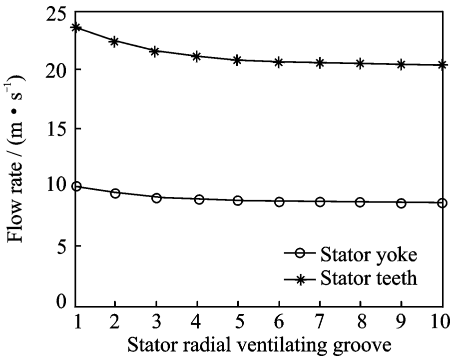

Fig. 6 Gas velocity distribution in stator radial ventilating grooves

3.2 Temperature field distribution

Figs. 9,10, respectively, show the tempera-

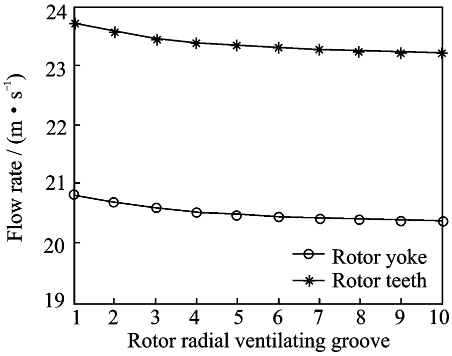

Fig. 7 Gas velocity distribution in rotor radial ventilating grooves

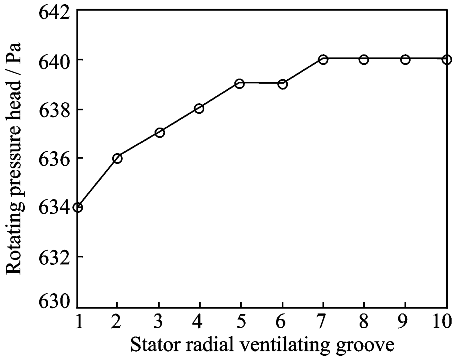

Fig. 8 Rotating head of rotor radial ventilation grooves

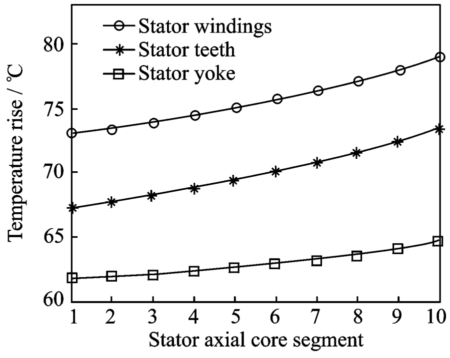

Fig. 9 Temperature distribution in stator core

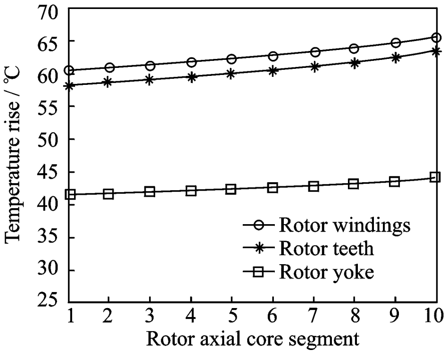

Fig. 10 Temperature distribution in rotor core

ture distribution of the windings, teeth and yoke in each core segment of stator and rotor. As shown in the figures, the temperature rise of different axial core segments of stator and the rotor is different. Temperature rise of the iron cores near the end is lower than temperature rise of those close to the middle position, which is consistent with the cooling gas flow flied distribution in the generator. The gas flow inside radial ventiation groove near the iron core is greater, so more heat is taken away by the cooling air, which results in lower temperature of the iron cores beside the radial ventilation groove. According to the simulation results, it can be seen that, for the single core of either stator or rotor, the temperature rise of windings is higher than that of teeth core, while the temperature rise of teeth core is higher than that of yoke core. This is because the loss of windings is higher than that of teeth core, while the loss of teeth is higher than that of yoke core. And the heat dissipation area of the yoke core is obviously larger than that of the teeth core and windings.

In this paper, the generator insulation class is B, under which the temperature rise limit of stator windings is 80 ℃ according to GB755[12]. According to the FLOWMASTER simulation, the average temperature rise of the generator stator winding is 75.515 8 ℃, which is within the temperature rise limit. In addition, the average temperature rise of the generator stator windings calculated by FLOWMASTER is compared with the result of theoretical calculation[13] and experiment, as shown in Table 1. The comparison shows that FLOWMASTER simulation result is more close to the measured value than the theoretical calculation result, the difference between which is only 0.687 7%. Therefore, the new method for fast simulation analysis of thermal fluid system inside generator based on the one-dimensional simulation software FLOWMASTER proposed in this paper has a high accuracy.

Table 1 Comparison of average temperature rise of stator winding by different methods

Calculation method	Temperature rise/℃
Simulation of FLOWMASTER	75.515 8
Theoretical calculation	77.223 4
Experiment	75.000 0

4 Conclusions

A new method for analysis of thermal fluid system inside generator is proposed in this paper based on the one-dimensional simulation software FLOWMASTER. Compared with the 3D simulation method, this method has obvious advantages in computing speed, which can help designers quickly get the flow rate and pressure distribution of cooling air as well as temperature rise of the key parts of the generator. According to the simulation results, we can obtain the following conclusions:

(1) The ventilation structure design of the 2.3 MW double-fed asynchronous generator meets the requirement of temperature rise limit.

(2) The central part of the generator is the weak link of the ventilation cooling system, which offers an instruction to the optimization of generator design.

(3) Comparison in Table 1 shows this simulation method has a higher precision, which provides a reference for the calculation of temperature rise of large generators.

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